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Agriculture, diversions, and drought shrinking Galilee Sea

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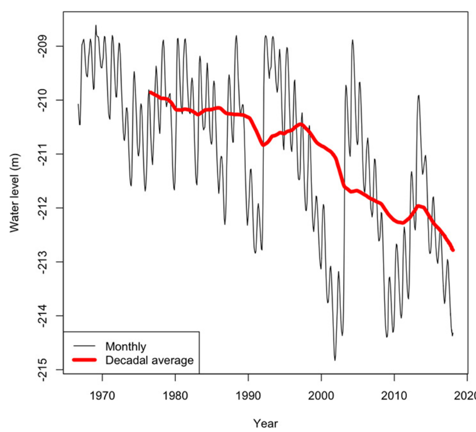
HIGHLIGHTS

- Lakes are disappearing on all inhabited continents, due to numerous factors.
- The Sea of Galilee, of religious significance to billions worldwide, is shrinking.
- Past work mistakenly implicated drought with the Sea's shrinkage.
- In fact, agriculture and flow diversion are primary causes of lake shrinkage.

GRAPHICAL ABSTRACT



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ABSTRACT

In water-limited regions worldwide, climate change and population growth threaten to desiccate lakes. As these lakes disappear, water managers have often implicated climate change-induced decreases in precipitation and higher temperature-driven evaporative demand—factors out of their control, while simultaneously constructing dams and drilling new wells into aquifers to permit agricultural expansion. One such shrinking lake is the Sea of Galilee (Lake Kinneret), whose decadal mean level has reached a record low, which has sparked heated debate regarding the causes of this shrinkage. However, the relative importance of climatic change, agricultural consumption, and increases in Lebanese water consumption, remain unknown. Here we show that the level of the Sea of Galilee would be stable, even in the face of decreasing precipitation in the Golan Heights. Climatic factors alone are inadequate to explain the record shrinkage of the Sea of Galilee. We found no decreasing trends in inflow from the headwaters of the Upper Jordan River located primarily in Lebanon. Rather, the decrease in discharge of the Upper Jordan River corresponded to a period of expanding irrigated agriculture, doubling of groundwater pumping rates within the basin, and increasing of the area of standing and impounded waters. While rising temperatures in the basin are statistically significant and may increase evapotranspiration, these temperature changes are too small to explain the magnitude of observed streamflow decreases. The results demonstrate that restoring the level of the Sea of Galilee will require reductions in groundwater pumping, surface water diversions, and water consumption by irrigated agriculture.

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1. Introduction

In water-limited regions worldwide environmental and ecosystem demands are simultaneously threatened by climate change and in competition with human water requirements to satisfy urban, agricultural, and industrial demands of a growing global population (Vorosmarty et al., 2000; Vorosmarty et al., 2010). Impacts of agricultural water consumption on environmental flows are exacerbated by rising evaporative demand due to higher temperatures and in certain regions—including the already water starved Middle East—lower precipitation due to changing rainfall patterns as the Earth system warms (Waha et al., 2017). While technological advances such as desalinization have somewhat ameliorated water scarcity in certain locations (Shannon et al., 2008; Elimelech and Phillip, 2011; Ziolkowska, 2016), the impacts of water consumption in arid lands worldwide remains dire as demonstrated by the demise of the Aral Sea and Lake Chad and decades of sustained rapid retreat of the Dead Sea (Micklin, 1988; Vitousek et al., 1997; Coe and Foley, 2001; Micklin, 2007; AghaKouchak et al., 2015; Hillel et al., 2015) among a growing list of other desiccating lakes (Liu et al., 2013).

To date, drivers implicated in the desiccation of lakes within Earth's six inhabited continents, which might be referred to as the Aral Sea syndrome, have included agricultural water consumption, urban water requirements, mining, construction of dams, and climatic changes (Liu et al., 2013; Fazel et al., 2017). In North American lakes suffering from this syndrome including the Great Salt Lake, Owens Lake, and Walker Lake, the primary causes were non-climatic (Wurtsbaugh et al., 2017). Similarly, in attempting to distinguish between human and climatic impacts in Iran's Lake Urmia watershed, Fazel et al. (2017) observed that headwater flow regimes were unaltered while proximal to the lake significant land-use changes occurred over time, consistent with a non-climatic driver impacting lake levels. In contrast, in semi-arid northern China a combination of climatic and agricultural impacts were implicated in the desiccation of over 100 lakes, though covariance of temperature and precipitation may challenge attempts to statistically infer the relative importance of these factors (Liu et al., 2013). Other research has suggested that climatic warming impacts on large lakes have not yet been observed (Beeton, 2002).

In past cases where lakes have desiccated, negative consequences have been widespread, including creation of natural hazards, impaired environmental quality, and economic impacts. The Dead Sea perhaps holds the unfortunate distinction of serving as the preeminent case study of the unanticipated impacts of a declining sea level on hydrogeologic natural hazards; specifically, with this sea's rapid retreat, swarms of sinkholes formed (Arkin and Gilat, 2000; Yechieli et al., 2006; Gutiérrez et al., 2014; Kottmeier et al., 2016), swallowing roads, vehicles, caravans, groves of date palms, and unlucky people, while forcing authorities to fence off large tracts of land considered high risk for sink holes. The incision of wadis draining into the Dead Sea has created micro canyons that threaten the stability of roads and affects the ecosystem of the alluvial fans (Bowman et al., 2010). In addition to explicit natural hazards, lake desiccation is well known to impact environmental quality, as in the case of the Aral Sea, wherein dried salt from the bottom of the sea was transported in large dust storms, damaged agricultural areas, and caused respiratory problems (Micklin, 1988). Desiccation of a large inland sea also removes its modulating influence on the climate (Micklin, 2007). From an economic perspective, lakes can be economic engines, promoting revenue from tourism, recreation, and fisheries (Wurtsbaugh et al., 2017). Finally, in the presence of saline groundwater or brines, decreases in lake head can enhance the hydraulic gradient and consequent discharge of saline groundwater into a freshwater lake, thereby jeopardizing the safety of a historical source of drinking water (Rimmer et al., 1999).

However, the impacts of groundwater pumping on surface water flows are less straightforward. Historically, groundwater and surface water were not believed to interact (Phillips et al., 2011). Indeed, there is a physical basis for groundwater being isolated from surface water in the presence of low permeability rock—an aquiclude. In addition to this physical basis, there is an economic motive to assume that groundwater and surface water systems are isolated. Assuming that these systems are isolated would allow for liberal exploitation of subsurface water, with no fear of impacting the quality or quantity of surface water bodies. However, contamination of shallow wells by methane accessed by wells as much as two kilometers below the surface (Osborn et al., 2011) as well as groundwater pumping that has reduced flow in rivers or converted perennial rivers to ephemeral (Zume and Tarhule, 2008; Kustu et al., 2010; Phillips et al., 2011) demonstrate the critical importance of considering the impacts of subsurface extraction on surface water. Consequently, a mechanistic understanding of groundwater-surface water interactions is a critical prerequisite to sustainably managing surface water resources potentially impacted by subsurface water extraction. Methods to model streamflow depletion caused by groundwater pumping have included both analytically derived models for idealized scenarios (Cuthbert, 2014), depletion apportionment equations (Zipper Samuel et al., 2018), and physically based distributed numerical methods that couple representation of surface and subsurface hydrologic processes (Ferguson and Maxwell, 2012).

One such case study of global change impacts on environmental flows is the Sea of Galilee (Fig. 1), whose level has entered a sustained decline that is unprecedented in modern recorded history (Fig. 2). In the absence of an examination of the water balance, currently local water managers attribute this decline to climatic effects. This claim that observed lake declines can be attributed to climate—even in the presence of extensive agricultural water use—is not uncommon and is similar to claims regarding Lake Abert (Moore, 2016), Lake Poopo (Satgé et al., 2017), and Lake Urmia (AghaKouchak et al., 2015), before formal investigations were undertaken. However, the relative impacts of natural climatic variability, anthropogenic climate change, and agricultural water use remain unknown. Furthermore, any impacts on flows in the Upper Jordan River (UJR) due to water consumption changes in Lebanon remain undetermined.

The Sea of Galilee has considerable importance from numerous perspectives and consequently government has vested interest in its conservation. This Sea has biblical significance such that it and its environs are visited by one million Christian pilgrims annually (Zvulun, 2016). Historically, the Sea has been an important water source, with the National Water Carrier transporting freshwater from it to the drier central and southern regions. It supports a commercial fishery in addition to a unique aquatic ecosystem. Geopolitically, a 50–55 MCM yr^{-1} transfer of high quality drinking water to the Kingdom of Jordan is required from the Sea of Galilee as part of the 1994 Israel-Jordan peace treaty, though recently transfers have increased in association with the flight of Syrian refugees to Jordan. Israel is considered to be a leader in the realm of water management, whether it be in the agricultural or desalinization sectors—maintaining this position will require preserving the Sea of Galilee. Consequently, the State of Israel—through the Water Authority (Ministry of Energy), Ministry of Agriculture, Ministry for the Protection of the Environment, the Nature Reserves Authority, Ministry of Tourism, and Ministry of Foreign Affairs—has a vested interest in and responsibility for the future of this lake.

Therefore, the goal of this study was to improve understanding of global change impacts on the level of the Sea of Galilee. In pursuit of this goal we tested the working hypothesis of the Israel Water Authority—that the current low level of water in the Sea of Galilee is a consequence of several consecutive years of low rainfall (Givati and Rosenfeld, 2007; Markel, 2014; Markel et al., 2014)—along with a suite of alternative hypotheses: 1) Increased water consumption in the headwaters of the UJR primarily located in Lebanon has reduced downstream flows. 2) Rising temperatures due to climate change have increased evapotranspiration within the Jordan River valley. 3) Expansion of agriculture in the UJR watershed—including construction of

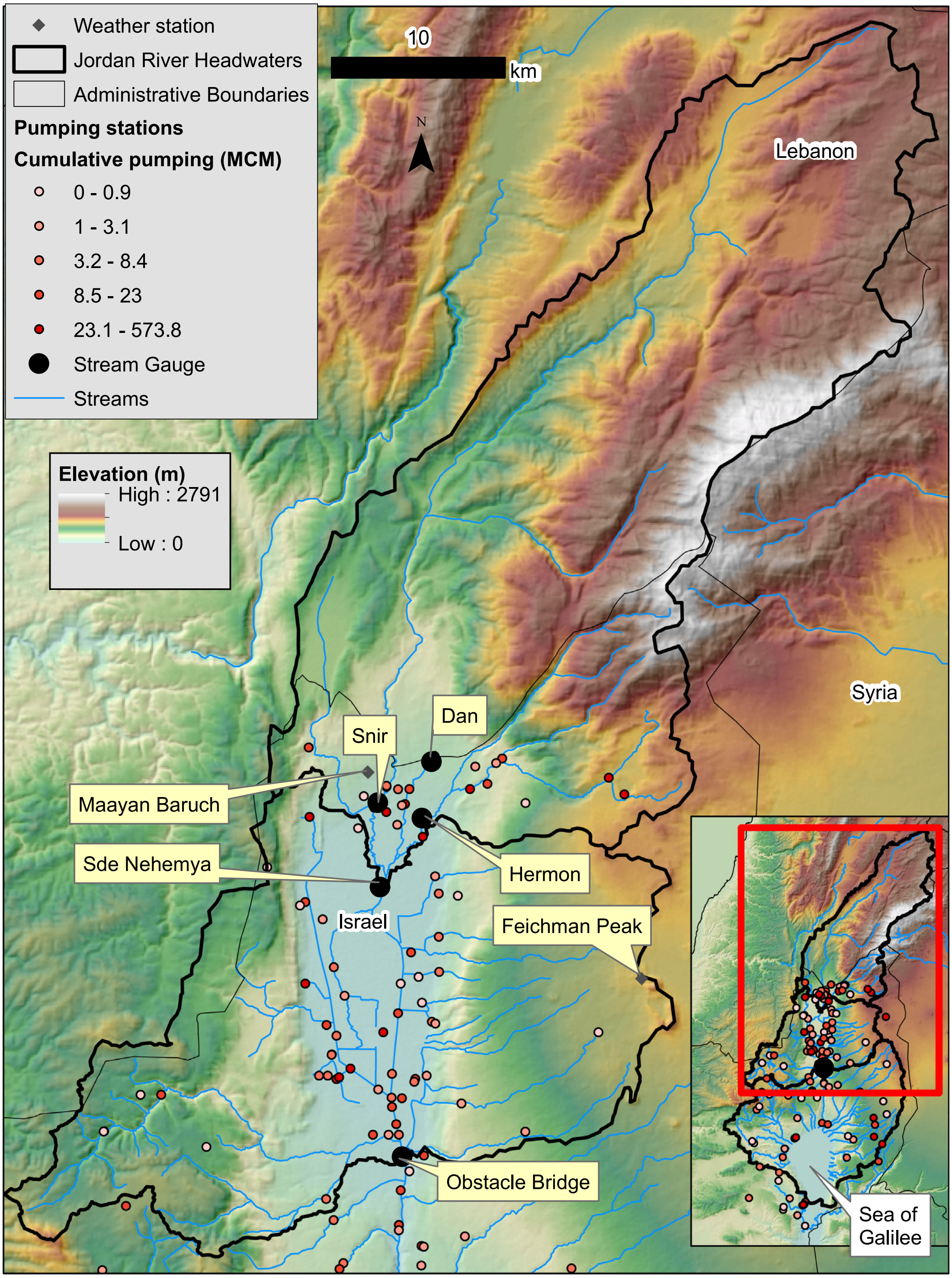

Fig. 1. Map of the headwaters of the Sea of Galilee including topographically delineated watershed boundaries and stream and rain gauges. Historical surface water pumping in the UJR and headwaters for water years 1975–2002.

new impoundments—are primarily responsible for reduced discharge from the UJR into the Sea of Galilee. Since the Israel Water Authority did not fulfill requests for contemporary surface water consumption data in the UJR basin, our study instead integrated data from five stream gauging stations, historical surface water consumption, two meteorological stations, the water budget of the Sea of Galilee, scores of moderate resolution remote sensing images, and groundwater pumping. With the exception of evaporation from the Sea, this study focuses on the hydrology of inflows from the UJR, leaving the economics, management considerations, and geopolitics of water withdrawals from the Sea to future research.

2. Study area

The Sea of Galilee is Israel's only freshwater lake with an area when full of 166 km^2. Water leaves the lake from several locations including near the Deganya dam—the lake's downstream outlet, where Israel is obligated by the 1994 peace treaty to provide 50 MCM of water to the

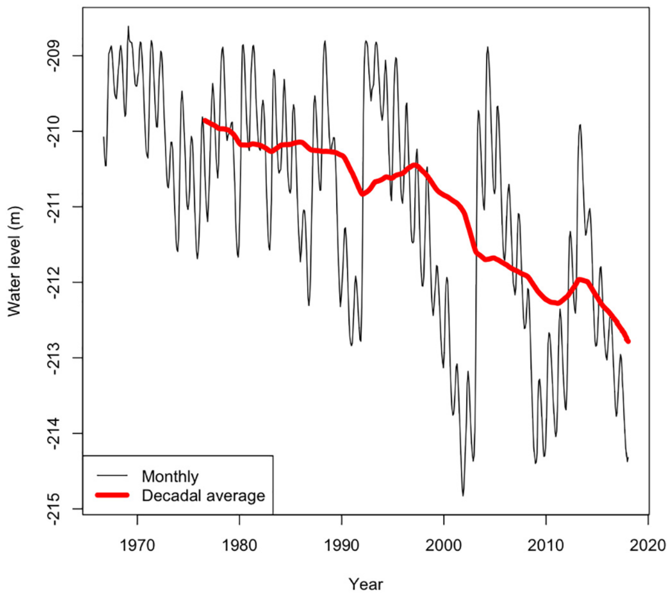

Fig. 2. The mean water level of the Sea of Galilee is dropping rapidly.

Kingdom of Jordan. According to Mekorot's water balance, which is solved following Assouline (1993), an estimated 240 MCM of water also leaves the lake by evaporation, which varies due to meteorological conditions as well as lake area; there is little disagreement regarding the magnitude of this term (Givati and Rosenfeld, 2007; Rimmer et al., 2011; Rimmer and Givati, 2014). The lowest level of the Sea of Galilee in recent years has been 214.87 m below sea level following the most serious drought in over a century, which occurred between 1998 and 2001; the effects of this drought were exacerbated by pumping water and flow diversion (Inbar and Bruins, 2004). From water years 1990–2016 mean flow into the sea from the UJR was measured to be 390 MCM, 65% of total inflows estimated following Assouline (1993). The remaining (estimated) 35% derive primarily from the watershed immediately surrounding the lake, though springs do discharge directly into the lake. As is expected for a Mediterranean regime inflows peak during the winter and early spring (January–April) and are lowest during the summer (July–August).

Hydrologic processes in the UJR watershed have been studied extensively to better understand orographic precipitation (Shamir et al., 2016), snowmelt dynamics (Gilad and Bonne, 1990; Samuels et al., 2010; Sade et al., 2011; Sade et al., 2014), extreme rainfall events (Samuels et al., 2009), global change impacts on the distribution of precipitation (Halfon et al., 2009; Givati and Rosenfeld, 2013; Ziv et al., 2013), climate change impacts on inflows to the Sea of Galilee (Rimmer et al., 2011), and streamflow generation in karst regions (Rimmer and Salingar, 2006; Hartmann et al., 2013). The tributaries of the UJR—the Snir, Dan, and Hermon—merge immediately upstream of the Sde Nehemya gauge and drain an 855 km^2 watershed. From Sde Nehemya the UJR continues to flow south through the Hula Valley—which is extensively used for agriculture—to the Obstacle Bridge gauge (1300 km^2), with several tributaries entering from the eastern Galilee to the west and from the Golan Heights to the east (Fig. 1).

Knowledge of the hydrogeology of the Jordan River headwaters remains limited by the political situation in this transboundary watershed (Rimmer and Salingar, 2006). However, the Hermon aquifer—the primary source of the UJR—consists predominantly of thick Jurassic limestone with well-developed karst features (Gilad and Bonne, 1990; Edgell, 1997) that cause surface water to cross topographic boundaries (Rimmer and Salingar, 2006). The Golan Heights consists of a 750 m thick sequence of fractured Pliocene-Pleistocene basalts interspersed with clayey paleosols (Dafny et al., 2003; Dafny et al., 2006). As a consequence of the paleosols a series of perched aquifers may develop, though spring flows therefrom are believed to historically account for only 10 MCM yr^{-1}; these flows furthermore occur in direct response to precipitation with little or no summer baseflow (Dafny et al., 2006). Springs flowing from the regional aquifer historically yielded 50 MCM yr^{-1} (Dafny et al., 2006), though spring flows are perceived as having decreased for reasons that remain unknown. The Hula Valley (177 km^2), part of the Dead Sea Rift Valley, consists of 450 m of lacustrine sediments—limnic chalk, clay, and organic-rich marls—overlying Pliocene basalts (Hambright and Zohary, 1998). Additionally, there are layers of peat sediments formed during dry periods when swamp conditions occurred.

This study commences in 1970 when streamflow data become available, though water resources were by no means pristine at that time and since then have been developed aggressively. In the 1950s the Hula Drainage project drained the Hula Lake (12–14 km^2) and swamps that together occupied up to 60 km^2 (Hambright and Zohary, 1998). Decades later in 1994, in response to deteriorating agricultural conditions, environmental degradation, and ecological devastation, the Hula Reclamation Project was implemented. This project created a small lake (1 km^2) and raised water tables to within 75 cm of the land surface over 20 km^2 to prevent subsidence of peat soils with a 90 km canal network (Geenberg, 1993). However, determination of the hydrologic impacts of this project—including evapotranspiration increases—has been considered intractable due to data scarcity (Tsipris and Meron, 1998). Geochemically enriched waters emerging from this project are routed to the Enan Reservoir (6 MCM capacity), which was built in 1984 (Hambright and Zohary, 1998).

3. Methods

3.1. Statistical analyses

Statistical analyses aimed to identify the root cause of hydrologic trends and to predict what natural flows might have been in the absence of extensive anthropogenic perturbations. Having observed the precipitous decrease in the level of the Sea of Galilee, we analyzed pertinent climatic and streamflow variables for trends in central tendency using the non-parametric Mann Kendall trend test, subject to the admonition of Morin (2011) that climatic variability can mask existing trends. Since the Israel Water Authority did not make recent water consumption data available for this research, we instead found it necessary to statistically reconstruct the natural inter-annual hydrograph. Because peak water consumption in this basin tends to occur toward the end of the water year in July and August, we found that water consumption tends to reduce streamflow by the consumed volume the year following consumption. Since historical surface water consumption data were available water years 1975–2002, streamflow volumes (for water years 1976–2003) were adjusted accordingly. (Groundwater pumping data were available only from 2000 onward and pumping rates from 2000 to 2003 averaged 18 MCM.) Following this adjustment, a linear regression between adjusted streamflow (Q) and precipitation at the Maayan Baruch (P_{MB}) and Feichman Peak (P_{FP}) rain gauge was fit similar to Rimmer et al. (2011):

$$Q_i = \beta_0 + \beta_1 \cdot P_{MBi} + \beta_2 \cdot P_{FPi} + \beta_3 \cdot P_{MBi-1} + e_i.$$

A temperature term was considered for inclusion in this model, but its inclusion could not be justified as improving the model, so such a term was ultimately excluded. These methods facilitated a first order estimate of natural streamflow. All statistical analyses were executed in R (R Core Team, 2017).

3.2. Lake stage simulation

The purpose of lake stage simulation is to determine if differences between actual inflows from the UJR and predicted natural inflows

substantially influence lake stage. Simulating the water balance of the Sea of Galilee is complex because not all inflows are measured, and evaporation is not measured. The complexity in lake evaporation arises from storage of heat within the lake due to the depth of the water column (Rimmer et al., 2009) as well as local and regional atmospheric factors (Shilo et al., 2015). Here we calculate monthly evaporation from the lake as the product of lake area and evaporative flux as determined by Mekorot following Assouline (1993); since this approach of simultaneous solution of water, heat, and salt balances has not been applied prior to 1990 (Rimmer and Givati, 2014), simulations of the lake's water balance are not attempted for preceding years. Due to the lake's hypsometry, at each time step we recalculate the volume remaining in the lake and on that basis, the area of the lake subject to evaporation at the following time step. Simulations are run for the baseline scenario—observed flows from the UJR—and for a scenario of natural flows in the UJR. Because simulated natural flows are computed on a water year basis and monthly inflows are desirable, monthly inflow was estimated as the product of annual flow and the historic proportion of flow each month. Since the majority of inflows to the lake are from the UJR, all other inflows and outflows (excluding evaporation) are unchanged between simulations. Inflows from sources other than the UJR include direct rain (11%), springs simulated as part of water balance solution (9%), and flows from the Yarmmuch (33%); measured surface water inflows to the Sea of Galilee from sources other than the UJR account for <10% of the lake's inflows.

3.3. Remote sensing and evapotranspiration

In the absence of quantitative consumptive water use data we capitalize on the historic archive of moderate resolution Landsat imagery to infer the potential magnitude of changes in evapotranspiration due primarily to changes in irrigated agricultural area, which has a distinct spectral signature during the dry summer relative to other land cover classes (Ozdogan et al., 2006). NDVI (Normalized Difference Vegetation Index) is an effective means of assessing plant leaf biomass in that this band ratio attains a maximum value when chlorophyll absorption of red light peaks and healthy mesophyll tissue reflection of infrared light decreases (Campbell and Wynne, 2011). However, similar to irrigated agriculture, forests also yield high NDVI values. Despite its name, this index is also sensitive to water bodies, which produce negative NDVI values (Chipman and Lillesand, 2007). Both water bodies and agricultural fields typically yield continuous spatial patterns at the scale of Landsat pixels (30 m). We take these considerations into account in constructing an algorithm to determine changes in irrigated area during the Landsat record.

We first take a threshold approach to estimating changes in irrigated area (NDVI > 0.45) and standing water (NDVI < −0.1). Next, to avoid overestimation of irrigated areas by misclassification of forested areas, we limit the analysis to those pixels classified by Hansen et al. (2013) as unforested. These methods effectively classify irrigated agricultural fields and impounded water, but stray pixels and small pixel clusters remain that are inconsistent with spatially continuous agricultural fields or reservoirs. To remove these pixels, we iteratively (seven times) pass a three by three-pixel majority neighborhood filter over the dataset, effectively removing these stray pixels. By implementing these methods in Python using the arcpy site package of ArcGIS 10.6, we extracted growing season irrigated and impounded area time series (1984–2017) from remotely sensed Landsat-derived Level I at surface reflectance imagery (Masek et al., 2006) for the UJR watershed. We further extracted pixel quality assessment data and limited NDVI values to those clear sky scenes that were free from clouds and their shadows. We also extracted radiometric saturation data and limited the analysis to images with few or no saturated pixels. We estimate PET from daily minimum and maximum temperature data from the Har Knaan weather station along with extraterrestrial solar radiation following Hargreaves and Samani (1985); this equation is typically appropriate for application to most climates without calibration, especially when long-term values are sought (Hargreaves, 1994; Jensen et al., 1997; Hargreaves and Allen, 2003; Ball et al., 2004) and remains in widespread application (e.g., Wine et al., 2018). Finally, we estimate potential agricultural water consumption as the product of evaporation excess and irrigated or impounded area, as determined from Landsat.

4. Results

4.1. Drought hypothesis

According to the drought hypothesis, dry weather conditions explain the low level of the Sea of Galilee. Trend analysis of streamflow and runoff coefficient at Obstacle Bridge both revealed significant streamflow decreases from 1971 to 2016 (Table 1). Trend analysis of rain yielded mixed results with no changes over time at Maayan Baruch (Fig. 3), but significant decreases over time at Feichman Peak in the Golan Heights (Fig. 4), though the latter trend relies only on 40 years of data, substantially less than the 50-year standard for assessing long-term trends. Fitting linear regressions to predict adjusted streamflow based on precipitation at each station suggested that predictions based on Feichman Peak precipitation were marginally better ($R^2 =$ 94.9 vs 94.4). The optimal model includes precipitation at both stations and lagged precipitation from Maayan Baruch ($R^2 = 96.6$, Fig. 5). This predicted natural streamflow can then drive a simulation of lake levels (Fig. 6). This simulation in turn demonstrates that drought does not explain shrinkage of the Sea of Galilee; under simulated natural streamflow input to the Sea of Galilee from the UJR, water levels remain stable, despite decreasing precipitation inputs at the Feichman station. From 1984 to 1988 the mean annual deficit between estimated natural flows and observed flows at Obstacle Bridge was 55 MCM, in contrast to 160 MCM for the 2012–2016 period (Fig. 6). The remainder of our study attempts to account for this deficit of 105 MCM yr^{-1}.

4.2. Headwaters hypothesis

According to the headwaters hypothesis, increased upstream water use by Lebanon in this transboundary watershed contributes to the observed low level in the Sea of Galilee. However, the absence of a trend in streamflow at the Sde Nehemya gage (Fig. 3) just downstream of the confluence of the tributaries of the Jordan River headwaters contradicts this hypothesis. While increases in Lebanese irrigated agriculture of about seven km^2 in the UJR watershed are apparent (Fig. 7), the potential increase in evapotranspiration due to these increased activities is small—about nine MCM—in comparison to hundreds of MCM in mean flow at Sde Nehemya. Furthermore, no major new impoundments are apparent in the UJR watershed within Lebanon. Consequently, we reject the hypothesis that increased Lebanese water use is primarily responsible for shrinking the Sea of Galilee. This observation allows us to consolidate this inquiry to the reach of the UJR between the Obstacle Bridge and Sde Nehemya gauges. Stationarity of streamflow at Sde Nehemya suggests an additional metric of flow alteration at the Obstacle Bridge gauge—the difference in streamflow between Obstacle Bridge and Sde

Table 1
Outcomes of Mann-Kendall trend tests on key variables; negative values indicate statistically significant decreasing trends.

Variable	p-Value
Precipitation (Maayan Baruch)	0.762
Precipitation (Feichman Peak)	−0.040
Temperature (Knaan Mountain)	<0.001
Streamflow (Obstacle Bridge)	−0.024
Runoff Coefficient (Obstacle Bridge)	−<0.001
Streamflow (Sde Nehemya)	0.910
Runoff Coefficient (Sde Nehemya)	0.691
Streamflow (Dan springs)	−<0.001

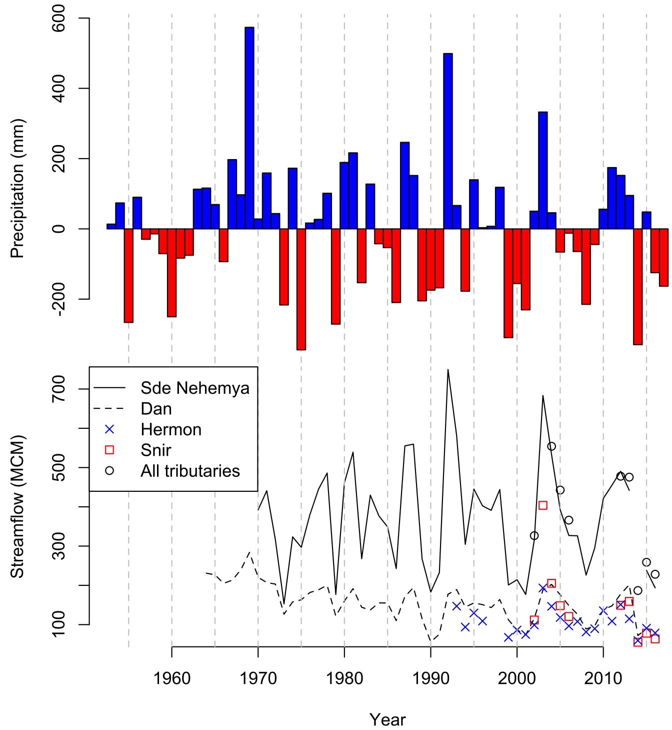

Fig. 3. Precipitation anomaly at Maayan Baruch (1953–2017) and streamflow at Sde Nehemya (1970–2016)—just downstream of the confluence of the Snir, Dan, and Hermon—are both stationary, contrary to widespread perceptions of an extended drought. There are no indications of a trend in median flows upstream of Sde Nehemya—the region that supplies 80% of flows to the UJR.

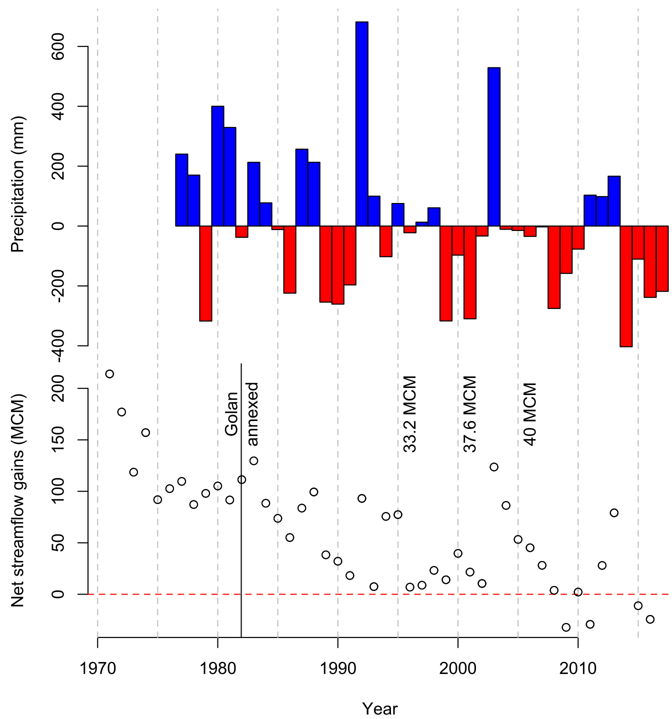

Fig. 4. Over time precipitation anomaly at the Feichman Peak gauge in the Golan Heights demonstrate a trend of decreased precipitation (1977–2017). This trend only partially explains decreases in net streamflow gain (1971–2016) between gauging stations at Sde Nehemya (upstream) and Obstacle Bridge (downstream). Similar precipitation anomalies in the Golan Heights yield differing net streamflow gains in the 1970s versus recent years. This decrease in streamflow gains occurred since Israel's annexation of the Golan Heights during which period new reservoirs were constructed, with maximum reservoir volume reaching 40 MCM by 2005.

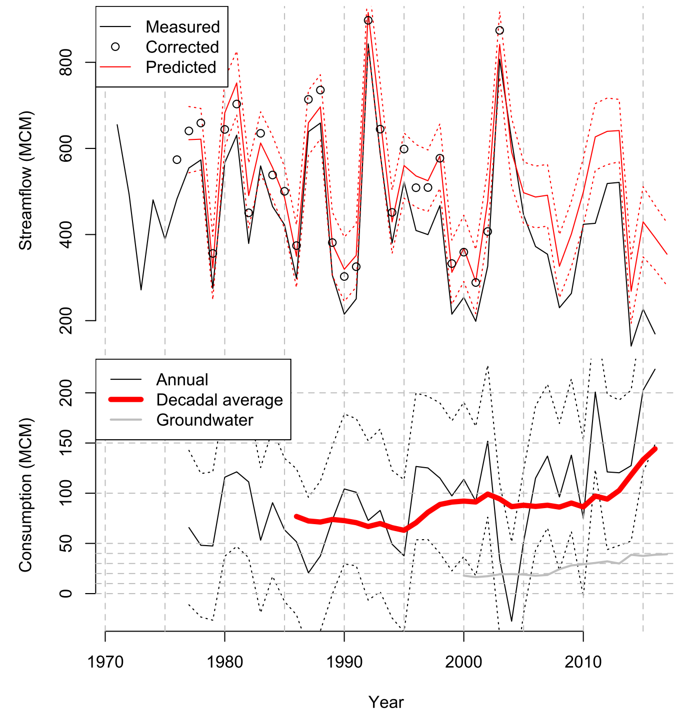

Fig. 5. Trends in measured streamflow, adjusted streamflow, and predicted natural streamflow (1971–2016) at Obstacle Bridge. Corrected streamflow (1976–2003) is the sum of measured streamflow and water consumption. Predicted natural streamflow (1977–2017) was fit to corrected streamflow. There is an increasing trend in the difference between predicted natural streamflow and measured streamflow, demonstrating increases over time in water consumption or diversion. 95% prediction confidence intervals are delineated around predicted streamflow and consumption (dotted lines).

Nehemya. Obstacle Bridge streamflow exceeded Sde Nehemya streamflow by 80 MCM annually during 1984–1988 and this difference dropped to 8 MCM in the 2012–2016 period, an annual 72 MCM decrease in streamflow at Obstacle Bridge.

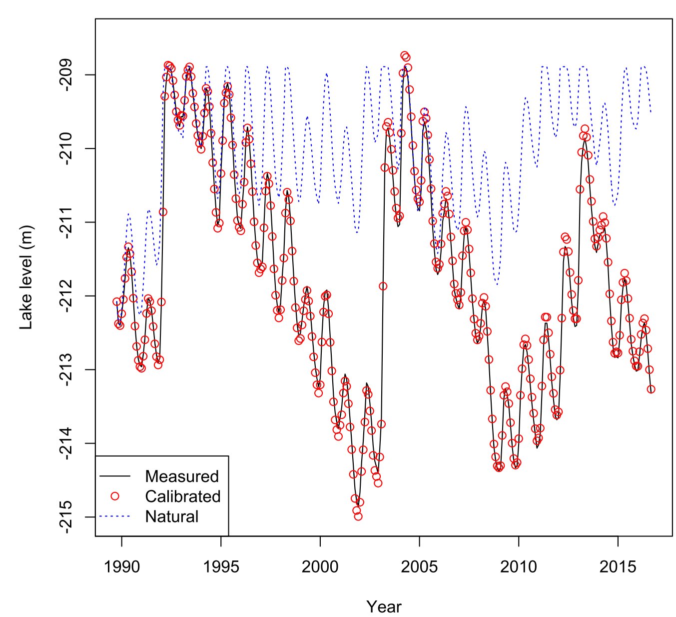

Fig. 6. Measured, calibrated, and natural levels of the Sea of Galilee. Natural levels are simulated based on simulated inflows from the UJR, predicted based on climatic factors alone. The difference between natural and calibrated curves is attributed to anthropogenic activities including surface water consumption, impoundment of surface water, and extraction of groundwater.

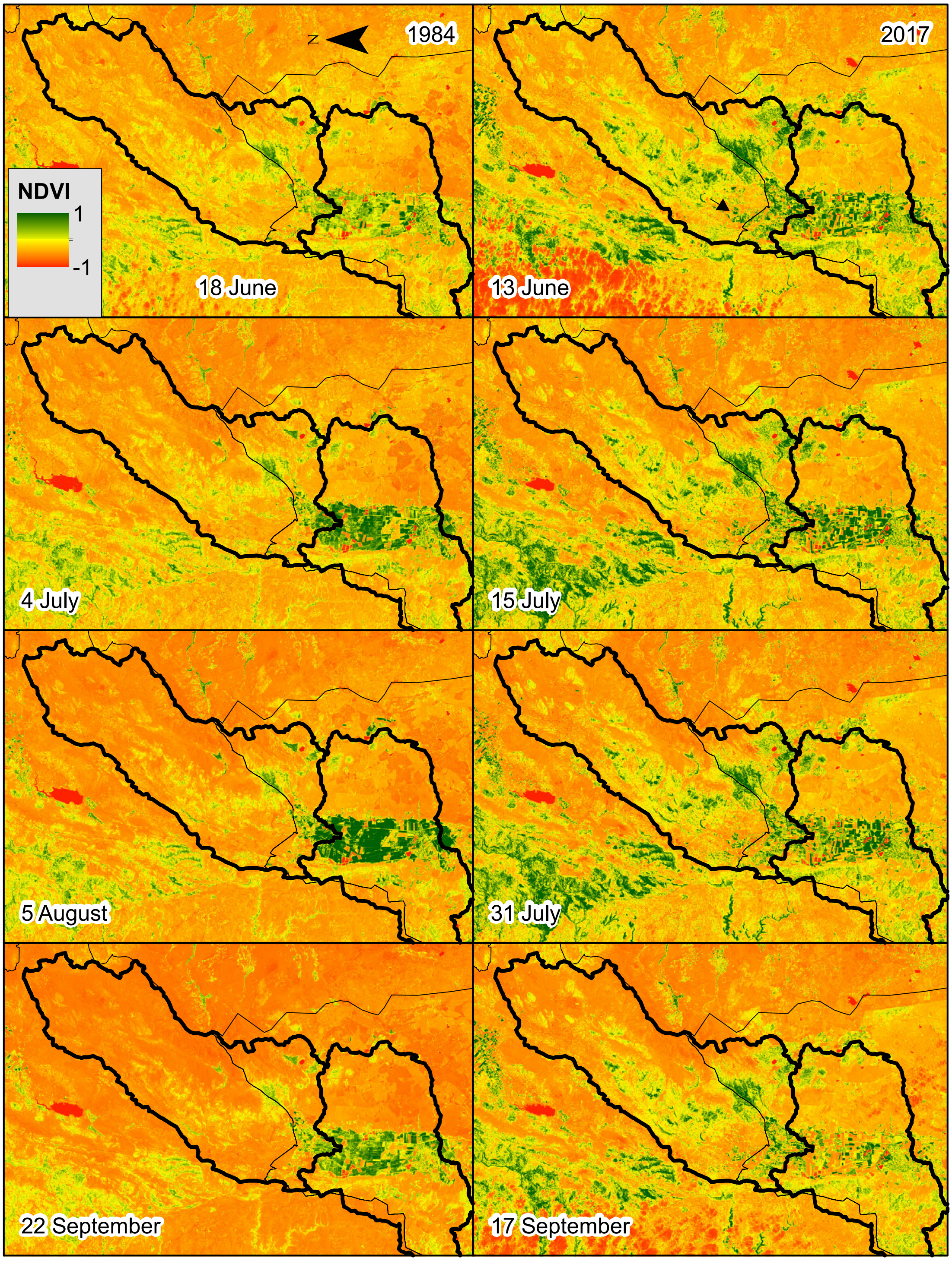

Fig. 7. Summertime Landsat-derived Normalized Difference Vegetation Index (NDVI) imagery demonstrating changes in irrigated areas (high NDVI) and surface water impoundments (low NDVI) from 1984 to 2017. Increases in Lebanese irrigated agriculture are indicated with an arrow on the June 2017 image. See Fig. 1 for location.

4.3. Rising temperatures hypothesis

According to the global warming hypothesis rising temperatures globally, including in the Jordan River headwaters, have increased evaporative demand; consequently, the same area of agricultural land would require increased water to supply crop water requirements. Indeed, we do observe significant increasing trends in air temperatures. From 1984 to 1988—the earliest five-year period with Landsat TM imagery—mean annual PET was 1130 mm and this value has increased to 1160 mm in the 2007–2016 period. This three cm increase affects all irrigated areas and impoundments in the watershed. In 1984 irrigated areas up gradient of the Obstacle Bridge gage comprised 160 km^2, which would correspond to global warming induced evaporation increases on the order of units of MCM—one to two orders of magnitude less than the 72–105 MCM sought.

4.4. Agricultural expansion hypothesis

Between the mid-1980s and the present, agriculture expanded within the watershed upstream of Obstacle Bridge and may account

for a 30 MCM yr^{-1} increase in consumption (Figs. 8–9, Table 2). This remote sensing based estimate assumes essentially maximal evapotranspiration rates (AET = PET), which are determined from considerations of environmental physics and may be considered an upper bound for agricultural evapotranspiration increases accounting for both increases in watershed irrigated area and rising evaporative demand. In the absence of change in storage, increases in remote-sensing estimated agricultural water consumption should be similar to the difference between natural and actual flows, unless large out of basin transfers of water are made. Instead, basin-wide statistical modeling suggests a 130 MCM yr^{-1} increase in the difference between natural and actual flows from the 1980s until the present. This result suggests the possibility that increases in water transfers out of the UJR basin—or groundwater pumping in areas affecting this basin—may exceed increases in agricultural water consumption within the basin. In fact, certain transfers out of the basin are well known—for example, pumping of groundwater from the Shamir wells to reservoirs on the Golan Heights. Given the high quality of freshwater from the Jordan River headwaters in comparison to the increasing solute concentrations in the Sea of Galilee, an economic incentive exists to consume or divert headwaters water before they reach the Sea of Galilee. Consequently, while agricultural water consumption within the basin is an important component of

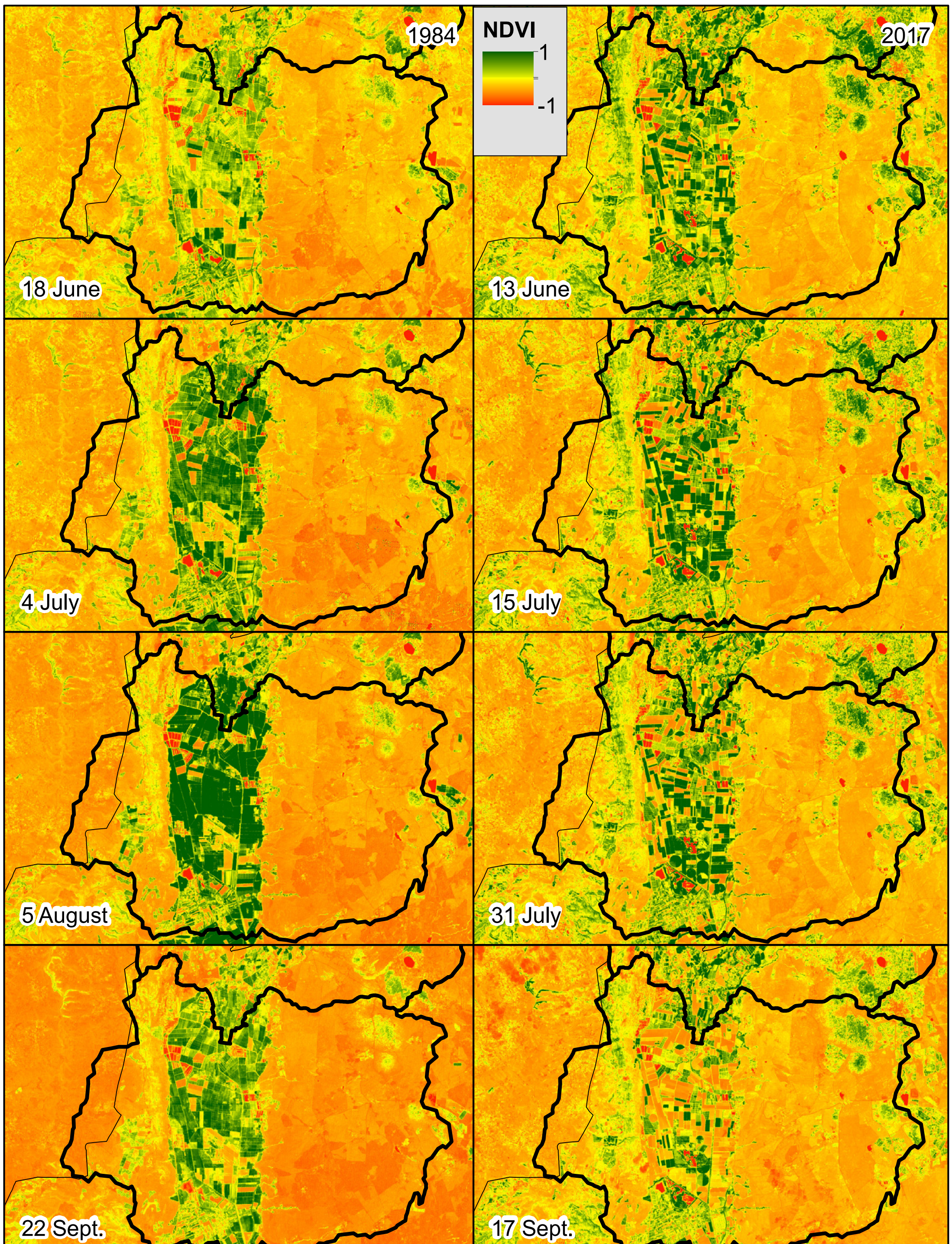

Fig. 8. Expansion of irrigated agriculture in the Golan Heights between 1984 and 2017, along with addition of new water supply reservoirs. See Fig. 1 for location.

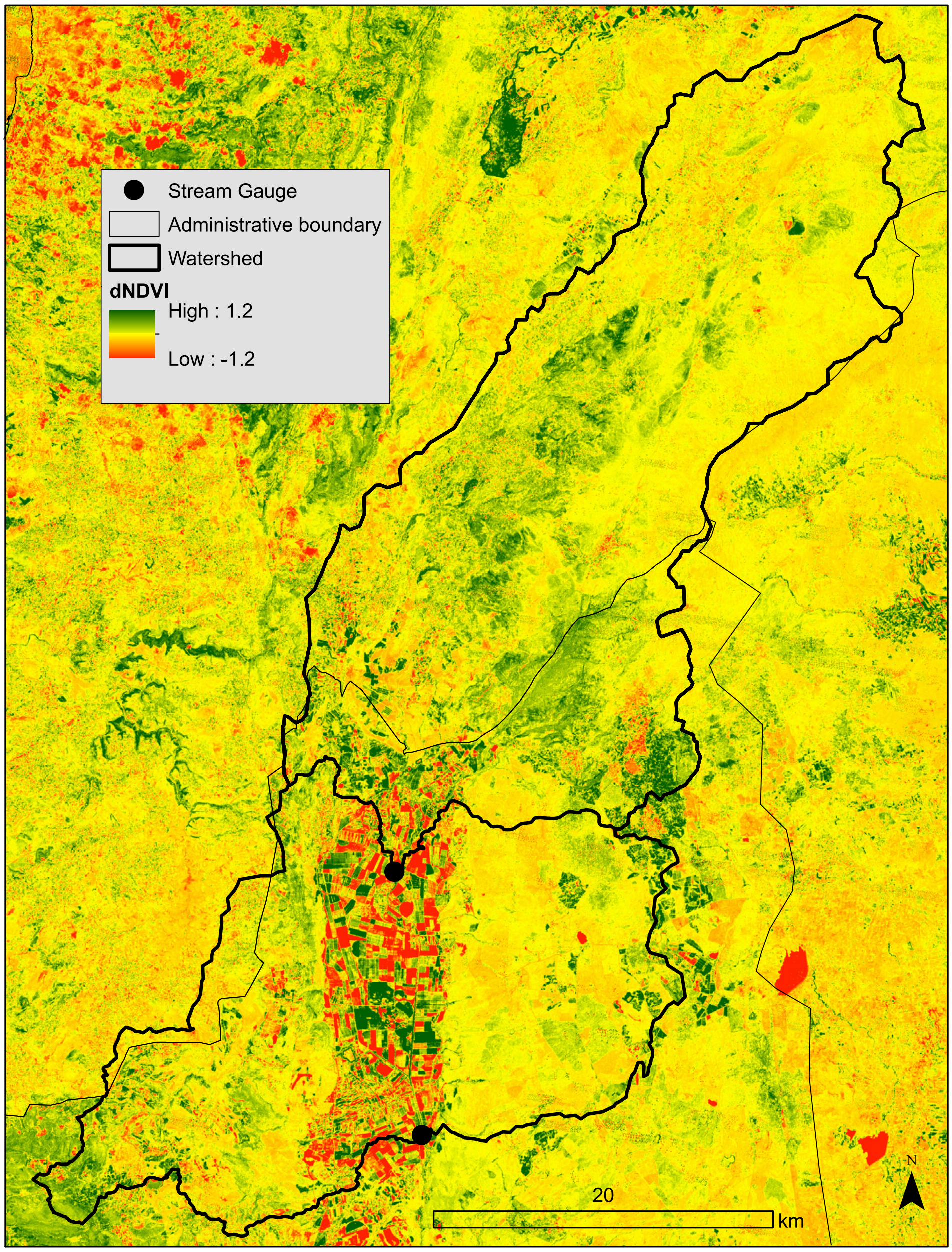

Fig. 9. NDVI difference ($NDVI_{July\ 4,\ 2013} - NDVI_{July,\ 4\ 1984}$) between 1984 and 2013; green areas indicate increased NDVI, highlighting areas of agricultural expansion.

Table 2
Evaporation excess, peak irrigated area, and potential agricultural water consumption in the Upper Jordan River watershed upstream of Obstacle Bridge have increased over the Landsat data record. The years presented here contained high quality Landsat images for three or more months.

Water year	Evaporation Excess	Peak irrigated area	Potential consumption Landsat	Model[a]
	mm yr^{-1}	km^2	MCM yr^{-1}	
1984	790	164	119	90
1987	821	155	119	21
2013	837	203	152	120
2015	849	190	136	203
2016	911	195	147	224
2017	1048	207	178	

[a] Consumption estimated as the difference between simulated natural and measured streamflow at Obstacle Bridge.

the water budget that has grown significantly since the 1980s, in terms of water budget changes since the 1980s another important change may involve increases in the transfer of high quality water from the Jordan River headwaters out of the basin.

5. Discussion

This study aimed to account for changes in the water balance that are shrinking the Galilee Sea. However, after testing four hypotheses, we succeeded in localizing much of the change to a 15 km reach of the UJR, but did not have sufficient information to close the water balance within this reach. This extremely complex problem can be broken down into two queries: How much water is missing at Obstacle Bridge and what accounts for this missing water? Both are difficult queries, particularly in the absence of cooperation of governmental scientists, who also serve as stewards of most key datasets. The simple method for estimating water consumption as the difference between measured

and predicted natural streamflow actually agrees quite well with past reports indicating a 150 MCM yr^{-1} increase in water consumption between 1975 and 2016 (Tal, 2018), providing confidence in our approach which estimated 157 MCM yr^{-1}. The two estimates here of missing water are in the range 72–105 MCM. The 105 MCM basin-wide estimate accounts for the decreasing precipitation trend at the Feichman station, whereas the 72 MCM estimate superficially appears biased high due to the decreasing precipitation trend in the Golan Heights. If this bias high is related to the precipitation difference between 1984 and 1988 (876 mm) and 2012–2016 (667 mm), then perhaps the true quantity of missing water is closer to 55 MCM. However, groundwater pumping of 40 MCM within the areas of the Jordan River headwaters administered by Israel is difficult to interpret because it is unclear to what extent this has already influenced surface water flow, given groundwater pumping at a range of depths with potentially complex intervening hydrogeology. Given the depth of some of the groundwater pumping wells, it seems likely that impacts of groundwater pumping on surface water would be lagged, implying that any surface process-based estimate of missing water underestimates total rates of water consumption.

On the water consumption side the largest uncertainties are how much evapotranspiration transpired and whether the source of the evaporated water was one that affected flows past Obstacle Bridge—some waters are pumped from deep wells with unknown intermediate hydrogeologies, sourced from the eastern side of the Golan Heights, sourced down gradient of Obstacle Bridge, or perhaps even pumped from wells drilled outside of the basin's topographic boundaries, but in an aquifer that feeds springs flowing into the basin. With the understanding that water consumption issues are extremely complex in this basin, the aim here was to provide a first order approach that estimates the maximum water potentially consumed by increases in evapotranspiration in the basin. It is possible that this water consumption estimate used here of 1130–1160 mm yr^{-1} is high, with an estimated use of surface water for irrigation in neighboring Syria at 700 mm yr^{-1} (Muller et al., 2016). Others have suggested that evapotranspiration in this region does not exceed 820 mm yr^{-1} (Comair et al., 2012). Potential evapotranspiration estimates are intended for application to large well-watered expanses as opposed to situations in water-limited areas such as the Golan Heights, in which irrigated agriculture is surrounded by dry semi-arid terrain; presumably this condition could increase evapotranspiration relative to potential values. While increases in water use in existing agricultural areas are possible, including following the Hula Reclamation Project technologies currently in use in the area—extensive drip irrigation (Tal, 2006), reflective netting (Cohen et al., 1997), and pulsed irrigation are likely to decrease water consumption following implementation. Potential agricultural water consumption estimates here (for the UJR watershed) are not inconsistent with reported actual consumption of 150 MCM yr^{-1} for the Sea of Galilee's watershed (Sade et al., 2016). When Golan water consumption of 34 MCM yr^{-1} is added to Eastern Galilee agricultural water consumption of 23 MCM yr^{-1} (Sade et al., 2016), total agricultural water consumption is 55 MCM yr^{-1}—nearly equal to the water missing between Sde Nehemya and Obstacle Bridge. Regarding Lebanon, estimated water consumed by irrigated agriculture (nine MCM) is lower here than past estimates of 20 MCM yr^{-1}(Rimmer and Givati, 2014).

While past research has observed lake shrinkage correlated with rising temperatures (Liu et al., 2013; Fathian et al., 2014; Fathian et al., 2016), none of these studies have demonstrated any physical mechanism by which rising temperatures might serve as a primary driver of lake shrinkage. Confusion regarding the role of temperature in the water balance of a water-limited system may occur stemming back to the environmental physics of radiation partitioning at the land surface. If the land surface is dry then absorbed incident radiation is converted to sensible heat, whereas if the land surface is wet this radiation is converted to latent heat as liquid water is evaporated. This fundamental principle of environmental physics explains why wet years generally are cooler than dry years, and also why rising temperatures have been erroneously ascribed responsibility for lake desiccation as in Fathian et al. (2016): "streamflow in Urmia Lake basin is more sensitive to changes in temperature than those of precipitation". While sufficient temperature rise might cause increased evaporation within lakes and their watersheds to impact lake water balances, to date such a mechanism has not been proven by physically based methods to be a primary driver of lake shrinkage.

When physical processes in the UJR headwaters, agricultural areas, and the lake itself are considered it becomes apparent that the rising trend in annual temperatures in the UJR watershed is a background condition of the Sea of Galilee's shrinkage, and not a primary driver. A range of hydrological processes potentially relevant to the UJR watershed promote streamflow generation under reduced influence from rising temperatures (Berghuijs et al., 2016), contrary to widespread conceptions (Table 3). Furthermore, numerical modeling of climate change impacts have not predicted substantial near-term streamflow changes (Samuels et al., 2010) or have indicated a wide amplitude of variability in predictions (Rimmer et al., 2011). Similarly evaporation from the lake surface is a complex process dependent on synoptic atmospheric conditions (Shilo et al., 2015), wind speed and dynamics (Assouline and Mahrer, 1993; Avissar and Pan, 2000), and local microclimate (Assouline and Mahrer, 1996) in addition to air temperature. Consequently, predicted increases in evaporation from the Sea of Galilee over time are small 0.10–0.25% per year (Rimmer et al., 2011).

The Sea of Galilee's current plight is a classic case of tragedy of the commons (Hardin, 1968), in which a common pool resource owned by all is exploited by all and protected by none. Indeed, it is the role of government to protect such common pool resources for the good of society. While Israel has laws to protect overexploitation of water resources (Laster and Livney, 2009), prior to publication of this report the Galilee Sea's shrinkage was attributed primarily to drought (Givati and Rosenfeld, 2007; Markel, 2014). In addition to issues related to scientific basis, Israel's water law framework has been criticized as fragmented and subject to political pressures to over-allocate water resources (Laster and Livney, 2009). Human population growth has been implicated as a key concern in maintaining sustainable natural resource allocations, a challenge expected to persist in coming decades (Laster

Table 3
Factors that influence the importance of evaporative demand variations in controlling groundwater recharge or streamflow generation in headwater regions. While rising temperatures are widely perceived as necessarily increasing evapotranspiration, a variety of processes complicate this relationship.

Process	Mechanism of action
Rooting depth	Generally climate, including temperature, is important to groundwater recharge, though the climatic control is modulated by root zone soil water storage capacity (Wine et al., 2015) with the influence of evaporative demand on groundwater recharge decreasing with reductions in storage capacity.
Preferential flow	It has increasingly been observed that preferential flow in natural soils is not the exception, but rather the rule (Doerr et al., 2009; Brooks et al., 2010; Wine et al., 2012a). Preferential flow may cause deeper wetting front penetration than would be expected of uniform or translatory flow (Šimůnek et al., 2003).
Precipitation phase	The relative phase of precipitation and evaporative demand may dictate that potential evapotranspiration is seasonally smaller than precipitation by an order of magnitude in Mediterranean climates where precipitation and evaporative demand are out of phase, even if at an annual scale evaporative demand exceeds precipitation by an order of magnitude as in a water-limited climate.
Grazing	Grazing is widespread and promotes infiltration excess overland flow (Wine et al., 2012b), which is not sensitive to evaporative demand because the Hortonian runoff occurs at a time scale that is small relative to the time required to evaporate significant water.
Fill and spill	If the hillslope storage threshold is small relative to rainfall events, then recharge or streamflow may be generated with little dependence on evaporative demand (Tromp-van Meerveld and McDonnell, 2006).

and Livney, 2009). Israel is by no means unique with regard to overexploitation of scarce water resources. Satellite-based algorithms (Allen et al., 2007) are now widely used by water managers in water-limited regions to verify compliance with water consumption allocations. Restoring the Sea of Galilee to a sustainable trajectory will require a commitment on the part of involved citizens, elected officials, and governmental agencies to allocating water within the finite natural limits of the Jordan River headwaters for the benefit of future generations.

6. Future directions

Despite the extensive hydrologic study of the Jordan River headwaters, key questions remain:

- Based on a suite of possible scenarios considering changes in climate, upstream water consumption, and geopolitics, how will the level of the Sea of Galilee change in the future?
- What impacts have occurred due to groundwater pumping? How does groundwater pumping interact with surface water flow? How has groundwater storage changed due to increases in groundwater pumping? How are deep and shallow groundwater connected? How does extracting water out of deep sources influence shallow sources?
- What controls observed changes in flows from springs? What are the relative roles of rising temperatures, changing precipitation regimes, and groundwater pumping?
- What are dominant streamflow generation processes in gauged watersheds—how will rising temperatures differently impact streamflow from geologically distinct areas, perhaps having different soil water storage capacities and hydrogeology?
- What are the actual evapotranspiration and recharge constants in the watershed—from the Hula Valley to Mt. Hermon—and their associated uncertainty? To what extent do existing evapotranspiration fields (e.g. Mu et al., 2011) and precipitation datasets (e.g. Menne et al., 2012) predict observed streamflow in the UJR?
- To what extent have widespread land-use and land-cover changes in Lebanon influenced streamflow response in the Jordan River headwaters?
- When all the measured headwater sources of the Sea of Galilee are taken individually—as opposed to considering the lumped response of the UJR—which model terms drive changes in flows?
- How much water does the Hula Reclamation Project consume?

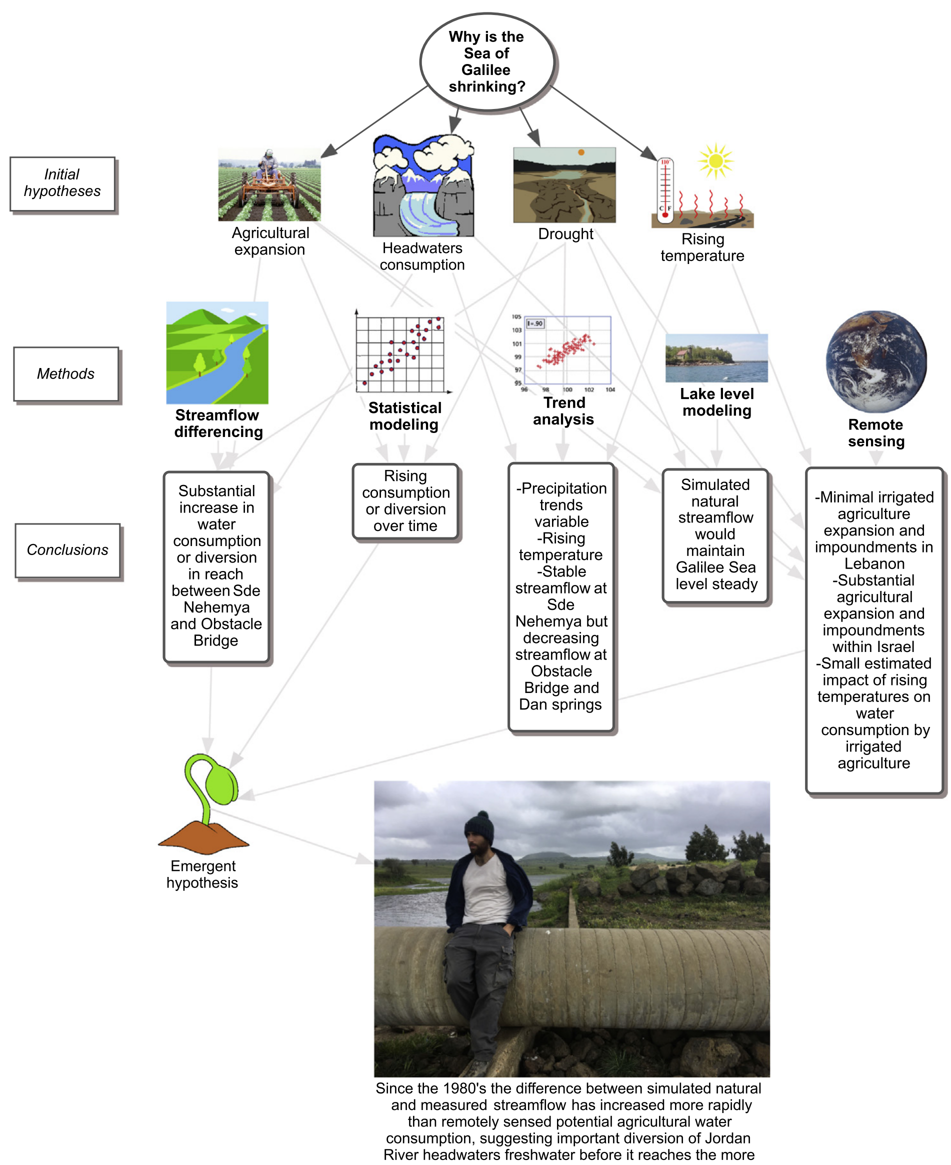

Fig. 10. Flow chart documenting methods used in testing each hypothesis and the conclusions attained.

- How has the distributed water budget of the headwaters of the Kinneret changed over time?
- How have water balance changes in the Sea of Galilee's watershed influenced solute concentrations within the Sea?

7. Conclusion

Globally, as in the case of the Sea of Galilee's shrinkage, we are increasingly challenged to elucidate the relative strength of competing cause-effect relationships, with simultaneous changes in precipitation, temperature, and agricultural water consumption, in this case with the added challenge of government secrecy regarding water consumption (Avni et al., 2015). By integrating remotely sensed imagery, meteorological data, streamflow measurements, and historical water consumption data, we demonstrate that while increased Lebanese water consumption, rising temperatures, and drought are indeed background conditions to the Sea of Galilee's shrinkage, even in the face of these factors its level would be stable (Fig. 10). This conclusion is strengthened by five independent lines of evidence—remote sensing showing minimal expansion of irrigated agriculture in Lebanon, statistically stable median precipitation at Maayan Baruch, statistically stable streamflow at Sde Nehemya, consideration of the headwaters springs whose discharge confirms the accuracy of Sde Nehemya streamflow measurements, and watershed-wide modeling of natural streamflow upstream of Obstacle Bridge used to force a lake level model. All of these lines of evidence point to water management changes—localized to the section of the Upper Jordan River watershed administered by Israel—as the primary drivers of the Galilee Sea's rapid shrinkage. Clearly agricultural water consumption is an important and increasing driver of the Galilee Sea's shrinkage, as demonstrated by remote sensing. Furthermore, the difference between simulated natural flows and observed flows at Obstacle Bridge grew much more rapidly than increases in potential agricultural water consumption, consistent with increases in diversion of high quality freshwater before such water would reach the Galilee Sea, whose waters have been experiencing an increase in dissolved constituents. The results demonstrate that conserving the Sea of Galilee would be feasible in the presence of management policies giving greater weight to the Sea of Galilee's inherent value—as a source of water security in the face of great climate uncertainty, an aquatic ecosystem, a site of recreation, a location of religious significance, and a source of tourism income—over economic interests that favor maximizing water consumption.

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References

AghaKouchak, A., Norouzi, H., Madani, K., Mirchi, A., Azarderakhsh, M., Nazemi, A., Nasrollahi, N., Farahmand, A., Mehran, A., Hasanzadeh, E., 2015. Aral Sea syndrome desiccates Lake Urmia: call for action. J. Great Lakes Res. 41, 307–311. https://doi.org/10.1016/j.jglr.2014.12.007.

Allen, R.G., Tasumi, M., Trezza, R., 2007. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) - model. J. Irrig. Drain. Eng. Asce 133, 380–394. https://doi.org/10.1061/(asce)0733-9437(2007)133:4(380).

Arkin, Y., Gilat, A., 2000. Dead Sea sinkholes - an ever-developing hazard. Environ. Geol. 39, 711–722.

Assouline, S., 1993. Estimation of lake hydrologic budget terms using the simultaneous solution of water, heat, and salt balances and a Kalman filtering approach - application to Lake Kinneret. Water Resour. Res. 29, 3041–3048. https://doi.org/10.1029/93wr01181.

Assouline, S., Mahrer, Y., 1993. Evaporation from Lake Kinneret: 1. Eddy correlation system measurements and energy budget estimates. Water Resour. Res. 29, 901–910. https://doi.org/10.1029/92WR02432.

Assouline, S., Mahrer, Y., 1996. Spatial and temporal variability in microclimate and evaporation over Lake Kinneret: experimental evaluation. J. Appl. Meteorol. 35, 1076–1084 (1988–2005).

Avissar, R., Pan, H., 2000. Simulations of the summer hydrometeorological processes of Lake Kinneret. J. Hydrometeorol. 1, 95–109. https://doi.org/10.1175/1525-7541(2000)001<0095:SOTSHP>2.0.CO;2.

Avni, N., Fishbain, B., Shamir, U., 2015. Water consumption patterns as a basis for water demand modeling. Water Resour. Res. 51, 8165–8181. https://doi.org/10.1002/2014wr016662.

Ball, R.A., Purcell, L.C., Carey, S.K., 2004. Evaluation of solar radiation prediction models in North America. Agron. J. 96, 391–397.

Beeton, A.M., 2002. Large freshwater lakes: present state, trends, and future. Environ. Conserv. 29, 21–38. https://doi.org/10.1017/s0376892902000036.

Berghuijs, W.R., Woods, R.A., Hutton, C.J., Sivapalan, M., 2016. Dominant flood generating mechanisms across the United States. Geophys. Res. Lett. 43, 4382–4390. https://doi.org/10.1002/2016gl068070.

Bowman, D., Svoray, T., Devora, S., Shapira, I., Laronne, J.B., 2010. Extreme rates of channel incision and shape evolution in response to a continuous, rapid base-level fall, the Dead Sea, Israel. Geomorphology 114, 227–237. https://doi.org/10.1016/j.geomorph.2009.07.004.

Brooks, J.R., Barnard, H.R., Coulombe, R., McDonnell, J.J., 2010. Ecohydrologic separation of water between trees and streams in a Mediterranean climate. Nat. Geosci. 3, 100–104. https://doi.org/10.1038/ngeo722.

Campbell, J.B., Wynne, R.H., 2011. Introduction to Remote Sensing. Guilford, New York.

Chipman, J.W., Lillesand, T.M., 2007. Satellite-based assessment of the dynamics of new lakes in southern Egypt. Int. J. Remote Sens. 28, 4365–4379. https://doi.org/10.1080/01431160701241787.

Coe, M.T., Foley, J.A., 2001. Human and natural impacts on the water resources of the Lake Chad basin. J. Geophys. Res. Atmos. 106, 3349–3356. https://doi.org/10.1029/2000jd900587.

Cohen, S., Moreshet, S., LeGuillou, L., Simon, J.C., Cohen, M., 1997. Response of citrus trees to modified radiation regime in semi-arid conditions. J. Exp. Bot. 48, 35–44. https://doi.org/10.1093/jxb/48.1.35.

Comair, G.F., McKinney, D.C., Siegel, D., 2012. Hydrology of the Jordan river basin: watershed delineation, precipitation and evapotranspiration. Water Resour. Manag. 26, 4281–4293. https://doi.org/10.1007/s11269-012-0144-8.

R Core Team, 2017. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Cuthbert, M.O., 2014. Straight thinking about groundwater recession. Water Resour. Res. 50, 2407–2424. https://doi.org/10.1002/2013wr014060.

Dafny, E., Gvirtzman, H., Burg, A., Fleischerc, L., 2003. The hydrogeology of the Golan basalt aquifer, Israel. Isr. J. Earth Sci. 52, 139–153. https://doi.org/10.1560/mxxa-cpjb-8lj9-r7fm.

Dafny, E., Burg, A., Gvirtzman, H., 2006. Deduction of groundwater flow regime in a basaltic aquifer using geochemical and isotopic data: the Golan Heights, Israel case study. J. Hydrol. 330, 506–524. https://doi.org/10.1016/j.jhydrol.2006.04.002.

Doerr, S.H., Woods, S.W., Martin, D.A., Casimiro, M., 2009. 'Natural background' soil water repellency in conifer forests of the North-Western USA: its prediction and relationship to wildfire occurrence. J. Hydrol. 371, 12–21. https://doi.org/10.1016/j.jhydrol.2009.03.011.

Edgell, H.S., 1997. Karst and hydrogeology of Lebanon. Carbonates Evaporites 12, 220. https://doi.org/10.1007/BF03175419.

Elimelech, M., Phillip, W.A., 2011. The future of seawater desalination: energy, technology, and the environment. Science 333, 712.

Fathian, F., Morid, S., Kahya, E., 2014. Identification of trends in hydrological and climatic variables in Urmia Lake basin, Iran. Theor. Appl. Climatol. 119, 443–464. https://doi.org/10.1007/s00704-014-1120-4.

Fathian, F., Dehghan, Z., Bazrkar, M.H., Eslamian, S., 2016. Trends in hydrological and climatic variables affected by four variations of the Mann-Kendall approach in Urmia Lake basin, Iran. Hydrol. Sci. J., 1–13 https://doi.org/10.1080/02626667.2014.932911.

Fazel, N., Haghighi, A.T., Klove, B., 2017. Analysis of land use and climate change impacts by comparing river flow records for headwaters and lowland reaches. Glob. Planet. Chang. 158, 47–56. https://doi.org/10.1016/j.gloplacha.2017.09.014.

Ferguson, I.M., Maxwell, R.M., 2012. Human impacts on terrestrial hydrology: climate change versus pumping and irrigation. Environ. Res. Lett. 7. https://doi.org/10.1088/1748-9326/7/4/044022.

Geenberg, J., 1993. Israel Restoring Drained Wetland, Reversing Pioneers' Feat. New York Times, New York.

Gilad, D., Bonne, J., 1990. The snowmelt of Mt Hermon and its contribution to the sources of the Jordan river. J. Hydrol. 114, 1–15. https://doi.org/10.1016/0022-1694(90)90072-6.

Givati, A., Rosenfeld, D., 2007. Possible impacts of anthropogenic aerosols on water resources of the Jordan river and the sea of galilee. Water Resour. Res. 43. https://doi.org/10.1029/2006wr005771.

Givati, A., Rosenfeld, D., 2013. The Arctic oscillation, climate change and the effects on precipitation in Israel. Atmos. Res. 132, 114–124. https://doi.org/10.1016/j.atmosres.2013.05.001.

Gutiérrez, F., Parise, M., De Waele, J., Jourde, H., 2014. A review on natural and human-induced geohazards and impacts in karst. Earth Sci. Rev. 138, 61–88. https://doi.org/10.1016/j.earscirev.2014.08.002.

Halfon, N., Levin, Z., Alpert, P., 2009. Temporal rainfall fluctuations in Israel and their possible link to urban and air pollution effects. Environ. Res. Lett. 4. https://doi.org/10.1088/1748-9326/4/2/025001.

Hambright, K.D., Zohary, T., 1998. Lakes Hula and Agmon: destruction and creation of wetland ecosystems in northern Israel. Wetl. Ecol. Manag. 6, 83–89. https://doi.org/10.1023/A:1008441015990.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853. https://doi.org/10.1126/science.1244693.

Hardin, G., 1968. The tragedy of the commons. Science 162, 1243. https://doi.org/10.1126/science.162.3859.1243.

Hargreaves, G.H., 1994. Defining and using reference evapotranspiration. J. Irrig. Drain. Eng. Asce 120, 1132–1139. https://doi.org/10.1061/(asce)0733-9437(1994)120:6(1132).

Hargreaves, G.H., Allen, R.G., 2003. History and evaluation of Hargreaves evapotranspiration equation. J. Irrig. Drain. Eng. 129, 53–63. https://doi.org/10.1061/(asce)0733-9437(2003)129:1(53).

Hargreaves, G.H., Samani, Z.A., 1985. Reference Crop Evapotranspiration From Temperature. 1. https://doi.org/10.13031/2013.26773.

Hartmann, A., Weiler, M., Wagener, T., Lange, J., Kralik, M., Humer, F., Mizyed, N., Rimmer, A., Barberá, J.A., Andreo, B., Butscher, C., Huggenberger, P., 2013. Process-based karst modelling to relate hydrodynamic and hydrochemical characteristics to system properties. Hydrol. Earth Syst. Sci. 17, 3305–3321. https://doi.org/10.5194/hess-17-3305-2013.

Hillel, N., Geyer, S., Licha, T., Khayat, S., Laronne, J.B., Siebert, C., 2015. Water quality and discharge of the lower Jordan river. J. Hydrol. 527, 1096–1105. https://doi.org/10.1016/j.jhydrol.2015.06.002.

Inbar, M., Bruins, H.J., 2004. Environmental impact of multi-annual drought in the Jordan Kinneret watershed, Israel. Land Degrad. Dev. 15, 243–256. https://doi.org/10.1002/ldr.612.

Jensen, D.T., Hargreaves, G.H., Temesgen, B., Allen, R.G., 1997. Computation of ETo under nonideal conditions. J. Irrig. Drain. Eng. Asce 123, 394–400. https://doi.org/10.1061/(asce)0733-9437(1997)123:5(394).

Kottmeier, C., Agnon, A., Al-Halbouni, D., Alpert, P., Corsmeier, U., Dahm, T., Eshel, A., Geyer, S., Haas, M., Holohan, E., Kalthoff, N., Kishcha, P., Krawczyk, C., Lati, J., Laronne, J.B., Lott, F., Mallast, U., Merz, R., Metzger, J., Mohsen, A., Morin, E., Nied, M., Rodiger, T., Salameh, E., Sawarieh, A., Shannak, B., Siebert, C., Weber, M., 2016. New perspectives on interdisciplinary earth science at the Dead Sea: the DESERVE project. Sci. Total Environ. 544, 1045–1058. https://doi.org/10.1016/j.scitotenv.2015.12.003.

Kustu, M.D., Fan, Y., Robock, A., 2010. Large-scale water cycle perturbation due to irrigation pumping in the US High Plains: a synthesis of observed streamflow changes. J. Hydrol. 390, 222–244. https://doi.org/10.1016/j.jhydrol.2010.06.045.

Laster, R., Livney, D., 2009. Israel: The evolution of water law and policy. In: Dellapenna, J.W., Gupta, J. (Eds.), The Evolution of the Law and Politics of Water. Springer Netherlands, Dordrecht, pp. 121–137.

Liu, H., Yin, Y., Piao, S., Zhao, F., Engels, M., Ciais, P., 2013. Disappearing lakes in semiarid northern China: drivers and environmental impact. Environ. Sci. Technol. 47, 12107–12114. https://doi.org/10.1021/es305298q.

Markel, D., 2014. Monitoring and management Lake Kinneret (Sea of Galilee) – preserving Israel's major surface water resource. EnviroGeoChimica Acta 1, 411–420.

Markel, D., Shamir, U., Green, P., 2014. Operational management of Lake Kinneret and its watershed. In: Zohary, T., Sukenik, A., Berman, T., Nishri, A. (Eds.), Lake Kinneret: Ecology and Management. Springer Netherlands, Dordrecht, pp. 541–560.

Masek, J.G., Vermote, E.F., Saleous, N.E., Wolfe, R., Hall, F.G., Huemmrich, K.F., Gao, F., Kutler, J., Lim, T.K., 2006. A Landsat surface reflectance dataset for North America, 1990–2000. IEEE Geosci. Remote Sens. Lett. 3, 68–72. https://doi.org/10.1109/lgrs.2005.857030.

Menne, M.J., Durre, I., Vose, R.S., Gleason, B.E., Houston, T.G., 2012. An overview of the global historical climatology network-daily database. J. Atmos. Ocean. Technol. 29, 897–910. https://doi.org/10.1175/jtech-d-11-00103.1.

Micklin, P.P., 1988. Desiccation of the Aral Sea - a water management disaster in the Soviet-Union. Science 241, 1170–1175. https://doi.org/10.1126/science.241.4870.1170.

Micklin, P., 2007. The Aral Sea disaster. Annual Review of Earth and Planetary Sciences, pp. 47–72.

Moore, J.N., 2016. Recent desiccation of western Great Basin saline lakes: lessons from Lake Abert, Oregon, U.S.A. Sci. Total Environ. 554-555, 142–154. https://doi.org/10.1016/j.scitotenv.2016.02.161.

Morin, E., 2011. To know what we cannot know: global mapping of minimal detectable absolute trends in annual precipitation. Water Resour. Res. 47. https://doi.org/10.1029/2010wr009798.

Mu, Q., Zhao, M., Running, S.W., 2011. Improvements to a MODIS global terrestrial evapotranspiration algorithm. Remote Sens. Environ. 115, 1781–1800. https://doi.org/10.1016/j.rse.2011.02.019.

Muller, M.F., Yoon, J., Gorelick, S.M., Avisse, N., Tilmant, A., 2016. Impact of the Syrian refugee crisis on land use and transboundary freshwater resources. Proc. Natl. Acad. Sci. U. S. A. 113, 14932–14937. https://doi.org/10.1073/pnas.1614342113.

Osborn, S.G., Vengosh, A., Warner, N.R., Jackson, R.B., 2011. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proc. Natl. Acad. Sci. U. S. A. 108, 8172–8176. https://doi.org/10.1073/pnas.1100682108.

Ozdogan, M., Woodcock, C.E., Salvucci, G.D., Demir, H., 2006. Changes in summer irrigated crop area and water use in southeastern Turkey from 1993 to 2002: implications for current and future water resources. Water Resour. Manag. 20, 467–488. https://doi.org/10.1007/s11269-006-3087-0.

Phillips, F.M., Hall, G.E., Black, M.E., 2011. Reining in the Rio Grande: People, Land, and Water. University of New Mexico Press, Albuquerque.

Rimmer, A., Givati, A., 2014. Hydrology. In: Zohary, T., Sukenik, A., Berman, T., Nishri, A. (Eds.), Lake Kinneret: Ecology and Management. Springer, Netherlands, p. 683.

Rimmer, A., Salingar, Y., 2006. Modelling precipitation-streamflow processes in karst basin: the case of the Jordan river sources, Israel. J. Hydrol. 331, 524–542. https://doi.org/10.1016/j.jhydrol.2006.06.003.

Rimmer, A., Hurwitz, S., Gvirtzman, H., 1999. Spatial and temporal characteristics of saline springs: sea of galilee, Israel. Ground Water 37, 663–673. https://doi.org/10.1111/j.1745-6584.1999.tb01158.x.

Rimmer, A., Samuels, R., Lechinsky, Y., 2009. A comprehensive study across methods and time scales to estimate surface fluxes from Lake Kinneret, Israel. J. Hydrol. 379, 181–192. https://doi.org/10.1016/j.jhydrol.2009.10.007.

Rimmer, A., Givati, A., Samuels, R., Alpert, P., 2011. Using ensemble of climate models to evaluate future water and solutes budgets in Lake Kinneret, Israel. J. Hydrol. 410, 248–259. https://doi.org/10.1016/j.jhydrol.2011.09.025.

Sade, R., Rimmer, A., Iggy Litaor, M., Shamir, E., Furman, A., 2011. The sensitivity of snow-surface temperature equation to sloped terrain. J. Hydrol. 408, 308–313. https://doi.org/10.1016/j.jhydrol.2011.08.001.

Sade, R., Rimmer, A., Litaor, M.I., Shamir, E., Furman, A., 2014. Snow surface energy and mass balance in a warm temperate climate mountain. J. Hydrol. 519, 848–862. https://doi.org/10.1016/j.jhydrol.2014.07.048.

Sade, R., Rimmer, A., Samuels, R., Salingar, Y., Denisyuk, M., Alpert, P., 2016. Water management in a complex hydrological basin—application of water evaluation and planning tool (WEAP) to the Lake Kinneret watershed, Israel. In: Borchardt, D., et al. (Eds.), Integrated Water Resources Management: Concept, Research and Implementation. Springer, p. 781.

Samuels, R., Rimmer, A., Alpert, P., 2009. Effect of extreme rainfall events on the water resources of the Jordan river. J. Hydrol. 375, 513–523. https://doi.org/10.1016/j.jhydrol.2009.07.001.

Samuels, R., Rimmer, A., Hartmann, A., Krichak, S., Alpert, P., 2010. Climate change impacts on Jordan river flow: downscaling application from a regional climate model. J. Hydrometeorol. 11, 860–879. https://doi.org/10.1175/2010jhm1177.1.

Satgé, F., Espinoza, R., Zolá, R., Roig, H., Timouk, F., Molina, J., Garnier, J., Calmant, S., Seyler, F., Bonnet, M.-P., 2017. Role of climate variability and human activity on Poopó Lake droughts between 1990 and 2015 assessed using remote sensing data. Remote Sens. 9. https://doi.org/10.3390/rs9030218.

Shamir, E., Rimmer, A., Georgakakos, K., 2016. The use of an orographic precipitation model to assess the precipitation spatial distribution in Lake Kinneret watershed. Water 8, 591. https://doi.org/10.3390/w8120591.

Shannon, M.A., Bohn, P.W., Elimelech, M., Georgiadis, J.G., Marinas, B.J., Mayes, A.M., 2008. Science and technology for water purification in the coming decades. Nature 452, 301–310. https://doi.org/10.1038/nature06599.

Shilo, E., Ziv, B., Shamir, E., Rimmer, A., 2015. Evaporation from Lake Kinneret, Israel, during hot summer days. J. Hydrol. 528, 264–275. https://doi.org/10.1016/j.jhydrol.2015.06.042.

Šimůnek, J., Jarvis, N.J., van Genuchten, M.T., Gärdenäs, A., 2003. Review and comparison of models for describing non-equilibrium and preferential flow and transport in the vadose zone. J. Hydrol. 272, 14–35. https://doi.org/10.1016/S0022-1694(02)00252-4.

Tal, A., 2006. Seeking sustainability: Israel's evolving water management strategy. Science 313, 1081–1084. https://doi.org/10.1126/science.1126011.

Tal, A., 2018. Addressing desalination's carbon footprint: the Israeli experience. Water 10. https://doi.org/10.3390/w10020197.

Tromp-van Meerveld, H.J., McDonnell, J.J., 2006. Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis. Water Resour. Res. 42, 1–11. https://doi.org/10.1029/2004wr003800.

Tsipris, J., Meron, M., 1998. Climatic and hydrological aspects of the Hula restoration project. Wetl. Ecol. Manag. 6, 91–101. https://doi.org/10.1023/A:1008459816898.

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of Earth's ecosystems. Science 277, 494–499. https://doi.org/10.1126/science.277.5325.494.

Vorosmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289, 284–288. https://doi.org/10.1126/science.289.5477.284.

Vorosmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., Davies, P.M., 2010. Global threats to human water security and river biodiversity. Nature 467, 555–561. https://doi.org/10.1038/nature09440.

Waha, K., Krummenauer, L., Adams, S., Aich, V., Baarsch, F., Coumou, D., Fader, M., Hoff, H., Jobbins, G., Marcus, R., Mengel, M., Otto, I.M., Perrette, M., Rocha, M., Robinson, A., Schleussner, C.-F., 2017. Climate change impacts in the Middle East and Northern Africa (MENA) region and their implications for vulnerable population groups. Reg. Environ. Chang. 17, 1623–1638. https://doi.org/10.1007/s10113-017-1144-2.

Wine, M.L., Ochsner, T.E., Sutradhar, A., Pepin, R., 2012a. Effects of eastern redcedar encroachment on soil hydraulic properties along Oklahoma's grassland-forest ecotone. Hydrol. Process. 26, 1720–1728. https://doi.org/10.1002/hyp.8306.

Wine, M.L., Zou, C.B., Bradford, J.A., Gunter, S.A., 2012b. Runoff and sediment responses to grazing native and introduced species on highly erodible Southern Great Plains soil. J. Hydrol. 450-451, 336–341. https://doi.org/10.1016/j.jhydrol.2012.05.012.

Wine, M.L., Hendrickx, J.M.H., Cadol, D., Zou, C.B., Ochsner, T.E., 2015. Deep drainage sensitivity to climate, edaphic factors, and woody encroachment, Oklahoma, USA. Hydrol. Process. 29, 3779–3789. https://doi.org/10.1002/hyp.10470.

Wine, M.L., Makhnin, O., Cadol, D., 2018. Non-linear long-term large watershed hydrologic response to wildfire and climatic dynamics locally increases water yields. Earth's Future 0. https://doi.org/10.1029/2018EF000930.

Wurtsbaugh, W.A., Miller, C., Null, S.E., Derose, R.J., Wilcock, P., Hahnenberger, M., Howe, F., Moore, J., 2017. Decline of the world's saline lakes. Nat. Geosci. 10, 816–821. https://doi.org/10.1038/ngeo3052.

Yechieli, Y., Abelson, M., Bein, A., Crouvi, O., Shtivelman, V., 2006. Sinkhole "swarms" along the Dead Sea coast: reflection of disturbance of lake and adjacent groundwater systems. Geol. Soc. Am. Bull. 118, 1075–1087. https://doi.org/10.1130/b25880.1.

Ziolkowska, J.R., 2016. Desalination leaders in the global market - current trends and future perspectives. Water Sci. Technol. Water Supply 16, 563–578. https://doi.org/10.2166/ws.2015.184.

Zipper Samuel, C., Dallemagne, T., Gleeson, T., Boerman Thomas, C., Hartmann, A., 2018. Groundwater pumping impacts on real stream networks: testing the performance of simple management tools. Water Resour. Res. 0. https://doi.org/10.1029/2018WR022707.

Ziv, B., Saaroni, H., Pargament, R., Harpaz, T., Alpert, P., 2013. Trends in rainfall regime over Israel, 1975–2010, and their relationship to large-scale variability. Reg. Environ. Chang. 14, 1751–1764. https://doi.org/10.1007/s10113-013-0414-x.

Zume, J., Tarhule, A., 2008. Simulating the impacts of groundwater pumping on stream-aquifer dynamics in semiarid northwestern Oklahoma, USA. Hydrogeol. J. 16, 797–810. https://doi.org/10.1007/s10040-007-0268-8.

Zvulun, R., 2016. The Sea of Galilee: A Biblical Lake in Recession. Haaretz, Israel.